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# Tantalus, a 240MeV Dedicated Source of Synchrotron Radiation, 1968-1986

## Abstract

Tantalus was a 240 MeV electron storage ring completed and commissioned in 1968. It was the first storage ring operated exclusively for the production of synchrotron radiation, although it was not designed for that purpose. As such, it influenced the operating pattern for subsequent dedicated sources of synchrotron radiation. Pioneering experiments using synchrotron radiation were carried out on this machine, and innovative instrumentation was produced there. It ceased operation in 1986.

## Keywords

Tantalus, storage rings

## Disciplines

Atomic, Molecular and Optical Physics | Condensed Matter Physics | Physics

## Comments

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## Tantalus, a 240 MeV Dedicated Source of Synchrotron Radiation, 1968–1986

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Tantalus was a 240 MeV electron storage ring completed and commissioned in 1968. It was the first storage ring operated exclusively for the production of synchrotron radiation, although it was not designed for that purpose. As such, it influenced the operating pattern for subsequent dedicated sources of synchrotron radiation. Pioneering experiments using synchrotron radiation were carried out on this machine, and innovative instrumentation was produced there. It ceased operation in 1986.

**Keywords:** Tantalus; storage rings.

### 1. The origins and construction of Tantalus

The early years of the use of synchrotron radiation are well documented elsewhere (Haensel & Kunz, 1967; Baldwin, 1975; Kunz, 1979). The radiation was first seen at the General Electric Corporation (Elder, Langmuir & Pollack, 1948) and first used as a source of radiation, in this case for absorption spectroscopy in the soft X-ray region, at Cornell University (Tomboulion & Hartman, 1956). Other early use took place at the National Bureau of Standards (Madden & Codling, 1962), Frascati (Cauchois, Bonnelle & Missoni, 1963) and DESY in Hamburg (Steinmann & Skibowski, 1966; Haensel, Kunz, Sasaki & Sonntag, 1968). Tantalus was to become the first electron accelerator or storage ring to be operated solely for the production of synchrotron radiation for use in experiments, primarily spectroscopic. In fact, it was the first storage ring used for synchrotron radiation, and a few types of experiments could be carried out more easily than on synchrotrons. However, the route to its construction and operation was not a direct one.

Midwest Universities Research Association (MURA) was formed in 1953 by 15 universities to promote and design a high-energy accelerator, a proton synchrotron, to be located in the Midwest. At its peak, over 100 physicists, engineers and support staff were employed by MURA. MURA began to design an electron synchrotron based on the fixed-field alternating-gradient (FFAG) concept for achieving high current. This was tested by the construction and study of a model electron accelerator based on this principle. Because the intent of MURA was the construction of a large synchrotron, a large tract of land suitable for such purposes had been acquired about 16 km southeast of the Madison campus of the University of Wisconsin. This land, overlooking Lake Kegonsa, near the small town of Stoughton, had an underlying bed of limestone with a rather flat surface, though the overlying clay and topsoil were rolling. The 45 MeV 'model' FFAG synchrotron was built in a concrete vault, largely underground for radiation shielding purposes,

with the control room located above in a metal prefabricated building on top of a small knoll. The model was a great success; currents of 10 A were achieved.

Meanwhile, Fred Mills and Ednor Rowe designed a small electron storage ring (Rowe & Mills, 1973; Rowe, Pruett, Steben & Winter, 1971). The purpose of the ring was to study phenomena resulting from higher current densities in storage rings, which had only recently been proposed. This ring was to operate at 240 MeV, with the 45 MeV model serving as its injector. The design current was 1 A. About the time the design was complete, a decision fatal to MURA was made in Washington. At the end of 1963, President Lyndon Johnson decided that the next large American accelerator, a machine Midwest particle physicists wanted, would be built at Batavia, IL, not at the MURA site. The political and socio-political events leading to this decision are described in Greenberg's book (Greenberg, 1967). This decision was to lead to the demise of MURA, and the loss of potential funding to build the 240 MeV storage ring.

Construction of the 240 MeV storage ring began in 1965 with MURA funds, but in March 1967 MURA effectively dissolved, leaving the new storage ring nearly complete, but with no more funding. Staff at MURA applied to the Atomic Energy Commission for funds to build the ring, justifying it first for its scientific merit, then as a training ground for future accelerator scientists and engineers. They were turned down.

In 1965, a subcommittee of the Solid-State Panel of the National Research Council began a study of the use of synchrotron radiation for research. They calculated the characteristics of the radiation expected from the 240 MeV ring, and described some of the experiments that could be performed with it. In their 1966 report (Brown, Hartman, Kruger, Lax, Smith & Vinyard, 1966) they recommended that this ring be completed, and that it be instrumented for spectroscopic experiments. As a result of this report, a

**Table 1**

Some parameters of Tantalus.

Energy	240 MeV
Injection energy	40 MeV
Bending radius	0.635 m
Ring circumference	9.38 m
Critical wavelength	257 Å
Critical energy	48.25 eV
R.f. frequency	31.956 MHz
Number of bunches	1
Bunch length	1 m
Pulse duration	3 ns
Horizontal emittance	230 nm rad
Vertical emittance	0.58 nm rad
Source width in bending magnet ( $\sigma_x$ )	1 mm
Source height in bending magnet ( $\sigma_y$ )	0.6 mm
Largest circulating current	260 mA
Typical beam half life	2 h

number of physicists and chemists were made aware of the construction of this storage ring. Several made visits to the site, and three made funding commitments for instrumentation to be placed on the ring. A proposal to the US Air Force Office of Scientific Research for funds to complete the storage ring was successful and the ring was completed in January 1968. The entity administering the project was the Physical Sciences Laboratory (PSL) of the University of Wisconsin. The ring was built in an extension of the vault for the model injector, created by adding walls and a roof to the driveway. The ring design originally had one viewport for observing visible synchrotron radiation, but the other possible ports were terminated in right-angle valves for connecting the vacuum tank to a roughing system. Two of

these, those pointing toward the largest empty region of the vault, were then equipped with straight-through valves, converting them to the first ports for the use of short-wavelength synchrotron radiation. Some of the characteristic parameters of Tantalus are listed in Table 1.

Tantalus achieved first stored beam in March 1968. Injection was very difficult. When it was time to fill the ring, only a single bunch of electrons from the FFAG could be accepted and accelerated. Increasing the current was achieved only by getting more electrons into that single bunch, or capturing a larger fraction of them. Increasing the current by adding electrons to the existing bunch, beam stacking, was not possible with the injection system of that time. A photograph of Tantalus at this stage is shown in Fig. 1. Fig. 2 is a drawing of the Tantalus layout at a later stage, with additional ports. (Those pointing 'backwards' were not used.)

The first three user groups were those of F. C. Brown (University of Illinois), Helmut Fritzsche (University of Chicago) and D. W. Lynch (Iowa State University and Ames Laboratory, USAEC). All used commercial monochromators: a Hilger 2 m grazing-incidence monochromator originally developed for plasma emission spectroscopy ('Gabriel mount'), a McPherson 0.5 m Seya-Namioka monochromator and a McPherson 1 m normal-incidence monochromator, respectively. A focusing mirror was provided by the Chicago group, and these three groups took turns on the one beamline that focused the radiation on an entrance slit. At this time, beam currents were less than 1 mA.

**Figure 1**

Tantalus. Seven of the eight bending magnets can be seen. The 'disk' on the right is the r.f. cavity. The University of Chicago's focusing-mirror chamber is in the foreground.

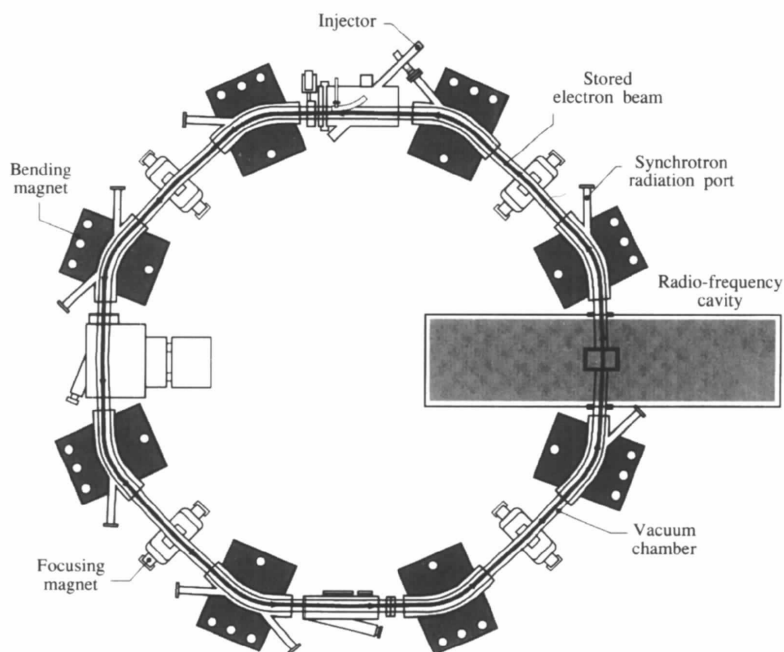
The Chicago and Ames groups were set up to measure reflectances in the 5–30 eV region, while the Illinois group was measuring transmission through thin films in the 50–150 eV region. The first real spectrum from a sample was obtained on 7 August 1968 by Ulrich Gerhardt, a postdoctoral visitor with the Chicago group. The ring current was about 1.4 mA.

The early experiments were difficult, for injection was not easy. Out of a 36 h week, perhaps only 5 h had beam present. The FFAG injector was old, frequently needing maintenance. The power supplies for the bending magnets of Tantalus were amplidyne, a type of motor-generator set, the bearings of which frequently needed replacement. Improvements were made over the next few years. In 1972 the building was enlarged to accommodate new beamlines. The vacuum tank was replaced with a new one containing more ports. More beamlines were added, with focusing mirrors and new monochromators (see later). A closed inflector replaced the open one, allowing the stacking of beams, *i.e.* multiple injections instead of a single shot, leading to a significant increase in beam current. By 1973 there were ten ports, and beam currents were up to about 50 mA, allowing additional types of experiments to be performed. A new injector, a 40 MeV microtron, was installed in 1974 (Rowe & Mills, 1973). Within a year currents then reached over 150 mA, and typically there was beam over 30 h per week. A stored beam of 260 mA was achieved in 1977. The removal of the FFAG synchrotron created much-needed floor space, though not for beamlines. In October 1974 funding from the Air Force Office of Scientific Research ceased, and funding from the National Science Foundation began.

## 2. Innovations in instrumentation

The monochromators used in the first experiments were commercial instruments, and all had drawbacks. None of them had a vacuum better than about  $2 \times 10^{-8}$  Torr, not as good as the vacuum in the storage ring. The grazing-incidence monochromator had a fixed entrance slit but the exit slit and detector just behind it moved along the Rowland circle on a tape. The samples for transmission measurements were mounted in front of the entrance slit. The Synchrotron Radiation Center (SRC), the entity operating Tantalus after the demise of MURA, began a program of instrument development that continues to this day. It was motivated by the desire for better instrumentation, with better vacuum, and with design changes to take advantage of unique characteristics of synchrotron radiation from a storage ring. SRC also wanted to develop its own beamlines for use by general users, those without their own monochromators. However, the beamlines owned by their developers, later to be termed PRT beamlines, were also available for use by general users. SRC staff designed and built an ultrahigh vacuum version of the McPherson 1 m normal-incidence monochromator. The McPherson instrument kept the fixed slits and grating on the Rowland circle by translating the grating toward the slits as the grating was rotated. This was performed by employing the same screw used to rotate the grating to translate the grating against a cam. The SRC design used two stepping motors, one for rotation and one for translation, with a computer to control both in order to keep the grating on the Rowland circle.

The grazing-incidence region presented more serious problems with scanning if the entrance and exit slits were to be kept fixed. The solution SRC chose was to use two



**Figure 2**  
Schematic drawing of Tantalus without beamlines or injector.

monochromators in series, the moving exit slit of the first serving as the moving entrance slit for the second. The first entrance slit and the second exit slit remained fixed during scanning. Each 3 m monochromator was adapted from the Vodar design, and the new one was called the 'double Vodar'. Its throughput was extremely low, and it was not used often.

Another early instrument was the so-called 'wavelength shifter', the first insertion device designed to tailor the spectrum of synchrotron radiation, installed in 1973 (Rowe & Mills, 1973; Trzeciak, 1971). This was a three-pole electromagnet with a central field up to 24.5 kG, higher than that of the bending magnets, so the spectrum was skewed to shorter wavelengths. Each end had a half-field magnet to return the beam to the steady-state orbit. The gap was small and the magnets were retracted during injection. Moving them back over the beam and turning them on without losing the beam proved very difficult. It was usually attempted only at the end of the day, and once beam was lost, time-consuming injection was not attempted. Nonetheless, it was energized successfully without loss of beam and the spectrum measured for comparison with calculations, one of the few uses of the double Vodar monochromator.

When beam currents became large enough for photoelectron spectroscopy, new monochromators were needed, designs emphasizing photon flux at the cost of resolution, although the first such measurements were made on a normal-incidence monochromator. SRC built several 1 m Seya-Namioka monochromators with dispersion in the vertical plane for the 5–40 eV region. These used cylindrical mirrors before the entrance slit and after the exit slit to reduce astigmatism, and also to allow the entrance and exit beams to travel horizontally. For the grazing-incidence region two user groups and SRC developed a toroidal-grating monochromator (Tonner, 1980), three of which were built. Rowland-circle monochromators offered higher resolution, but lower flux. The idea for one such monochromator, the 'grasshopper', began at SRC. The instrument was designed at SRC and built at the Physical Sciences Laboratory for the Xerox Palo Alto Research Center. It was installed at the Stanford Synchrotron Radiation Laboratory (Brown, Bachrach & Lein, 1978).

Angle-resolved photoemission soon followed with the modification of a commercial cylindrical mirror analyser by the insertion of a rotatable drum with an aperture limiting the range of azimuthal angles transmitted through the analyser (Knapp, Lapeyre, Smith & Traum, 1982). This modification subsequently became commercially available. Parallel-plate analysers were also used in the early angle-resolved photoemission measurements. Later, the display analyser was developed for use at SRC (Eastman, Donelon, Hien & Himpsel, 1980). This analyser used an ellipsoidal mirror as a low-pass filter for the photoelectrons and a spherical retarding grid as a high-pass filter. Thus, only electrons within a small, but variable, range of kinetic energies could pass through and be accelerated to a

phosphor screen. The resultant pattern could be stored for subsequent digitization and playback. Several display analysers have been constructed in recent years for use at other synchrotron radiation facilities.

### 3. Experiments

The earliest measurements were of optical transmission of thin films and reflectance of bulk solids. As the beam currents became larger than 50 mA other experiments became possible: photoelectron spectroscopy, modulation spectroscopy, photodissociation and fluorescence in gases. In a review of this type, it is not possible to cite more than a handful of the research publications emanating from Tantalus. In the steady-state mode of operation there were up to several hundred publications per year. Those measurements described below often were the first of their type carried out at Tantalus, and sometimes the first of their type anywhere in the world.

The first publication of results from each of the first three groups dealt with the absorption spectrum of  $14d$  electrons in alkali iodides (Fujita, Gähwiler & Brown, 1969), the reflectance spectra of several ionic crystals (Rubloff, Freeouf, Fritzsche & Murase, 1971) and the dielectric function of single-crystal Cd obtained from reflectance spectra (Bartlett, Lynch & Rosei, 1971).

Photoelectron spectroscopy began in 1971. This type of measurement requires a large monochromatic photon flux because of the small photoyield of most materials. The conventional mode of taking photoemission spectra, the only mode possible with atomic emission line sources, is to scan a kinetic energy window throughout the emitted spectrum while keeping the photon energy fixed. The resultant spectrum, an energy distribution curve (EDC), contains information about both the initial and final states. (If the electric dipole transition matrix elements are neglected the EDC is proportional to a convolution of the densities of states of the initial- and final-state bands.) The first photoemission measurements were made on films of Au in the 10–40 eV region, a wider energy range than studied heretofore (Grobman & Eastman, 1972). These data helped to settle an ongoing disagreement on whether the photoexcitations leading to photoemission were direct (momentum conserving) or indirect in favor of the former.

The synchrotron radiation continuum with a monochromator offers two new modes of data acquisition that help separate the roles of initial and final states. In the constant final-state (CFS) mode the electron energy analyser passes a fixed energy while the photon energy is scanned, thereby scanning through different initial states. In the constant initial-state (CIS) mode, the kinetic energy detected and the photon energy are scanned in synchronism. This allows the initial state, set by the energies at the start of the scan, to remain fixed while the final state is scanned. The three scans are shown schematically in Fig. 3.

The first implementation of both new modes was on Tantalus by the group of G. J. Lapeyre. Fig. 4 shows CIS

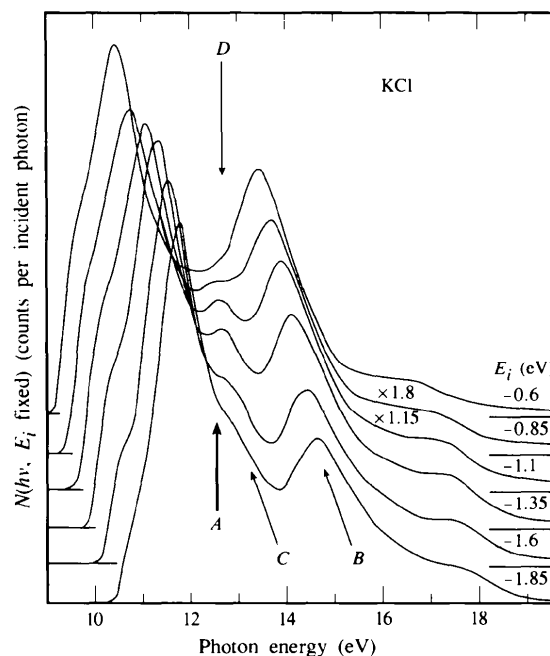
scans for KCl (Lapeyre, Anderson, Gobby & Knapp, 1974). The initial states selected are in the valence band. Peaks *A* and *B* and shoulder *C* occur at the same energy for all three initial states, they represent structure in the density of final states. They have different strengths due to changes in the electric dipole matrix elements. Peak *D* occurs at the same photon energy in each spectrum (not obvious in this figure). It was tentatively assigned to an autoionizing exciton based on photoelectrons in a higher conduction band, the band responsible for peak *B*, and a valence-band photohole.

Fig. 5 shows CFS scans for KI (Lapeyre, Baer, Hermanson, Anderson, Knapp & Gobby, 1974). The spectral region includes the threshold for photoexcitation of the K  $3p$  core level. The shaded peak,  $\Gamma$ , exhibiting the spin-orbit splitting of the K  $3p$  levels, appears in only one spectrum. It was assigned to the Auger decay of the core exciton based on photoelectrons at the bottom of the conduction band. The peak *X* was assigned to the core exciton based on a photoelectron at the higher conduction-band minimum at *X*. It is additionally lifetime-broadened due to rapid dissociation into electron-hole pairs.

With further increases in beam current and innovations in electron energy analyser design, angle-resolved photoemission became possible. Only a small fraction of the electrons collected in an angle-integrated measurement are collected in an angle-resolved measurement, so higher photon fluxes are required. In an angle-resolved experiment one obtains the wavevectors of the emitted electron in addition to the kinetic energies because the wavevector component parallel

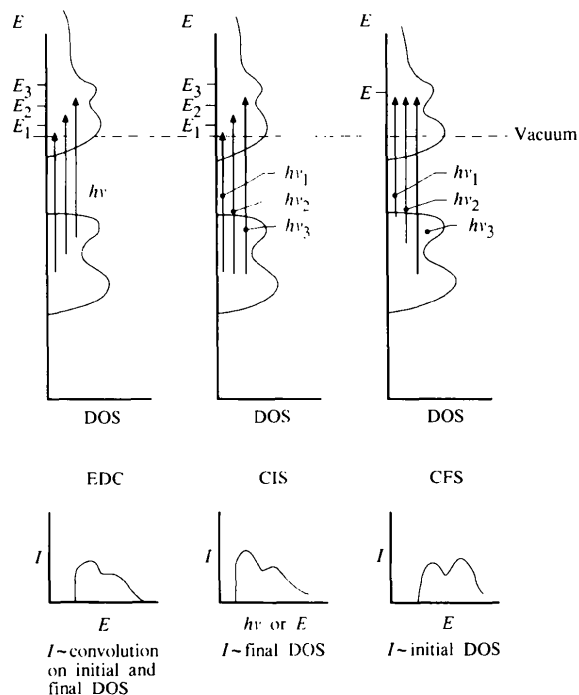
to a good surface of a single-crystal is conserved when the excited photoelectron escapes. (There are various schemes for determining the normal component of the wavevector.)

Smith, Traum, Knapp & Lapeyre (1976) carried out early angle-resolved photoelectron spectroscopy on 1T-TaS<sub>2</sub>, a



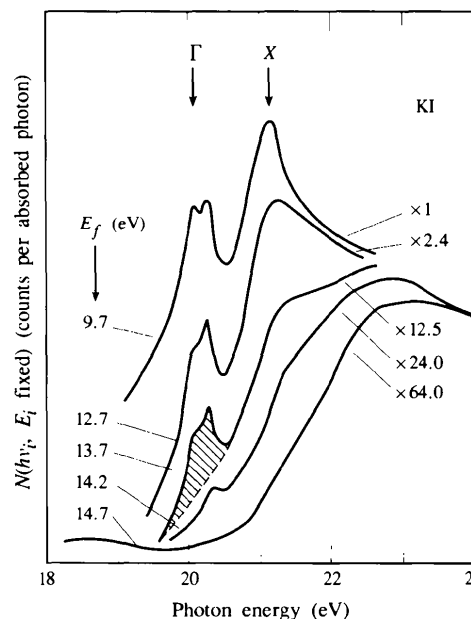
**Figure 4**

CIS scans, photocurrent *versus* final-state energies, taken on KCl at three initial-state energies (bottom). The top curve is the low kinetic energy part of an EDC, consisting of inelastically scattered electrons (Lapeyre, Anderson *et al.*, 1974).



**Figure 3**

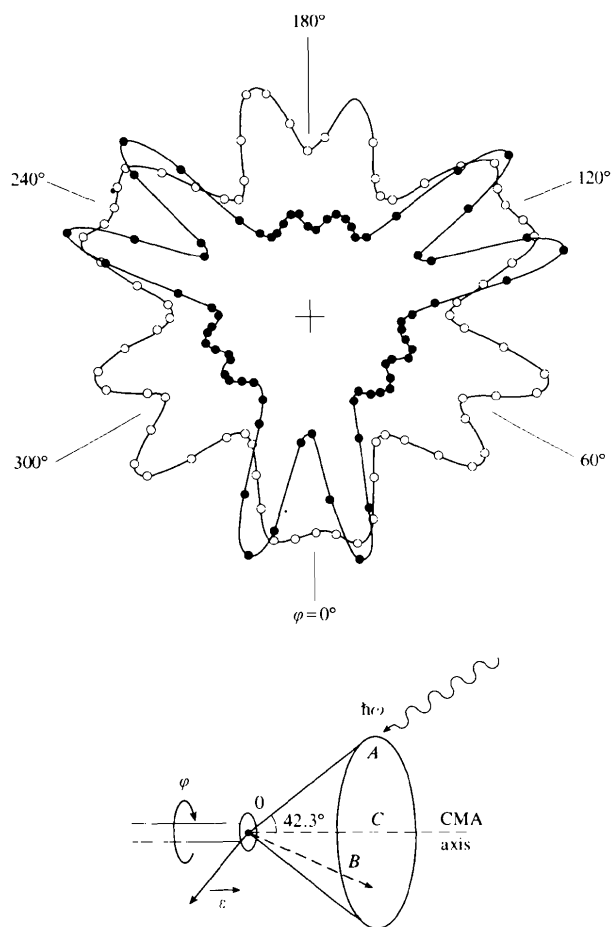
Schematic density of states for a crystal. The top row shows typical photoexcitations for three modes of photoelectron spectroscopy. The bottom row shows typical spectra for each.



**Figure 5**

CFS scans, photocurrent per absorbed photon *versus* photon energy, with varying electron kinetic energy, taken on KI for five final-state energies (Lapeyre, Baer *et al.*, 1974).

layered material. In addition to being able to tune the energy of the monochromated synchrotron radiation so as to excite  $3d$  core states, they used the polarization of the radiation to study the selection rules. Fig. 6 shows the two arrangements they used to obtain spectra as a function of azimuthal angle about the  $c$  axis of the single crystal, and two of those spectra. The radii in the spectra represent photoelectron current into a small solid angle as a function of azimuthal angle. The two geometries used correspond to collecting photoelectrons with components of wavevector in the plane of the surface that are perpendicular and parallel to the electric field of the incident photon. The large anisotropy and polarization dependence are evident in the figure. Such measurements soon led to a rapid growth of angle-resolved photoelectron spectroscopy. Examples of later work are the observation of the exchange splitting in Ni (much smaller than had been calculated) (Eastman, Himpsel & Knapp, 1978), and the energy bands of GaAs, mapped from angle-resolved photoelectron spectra for comparison with calculated energy bands (Fig. 7) (Chiang, Knapp, Eastman & Aono, 1979; Chiang, Knapp, Aono & Eastman, 1980).



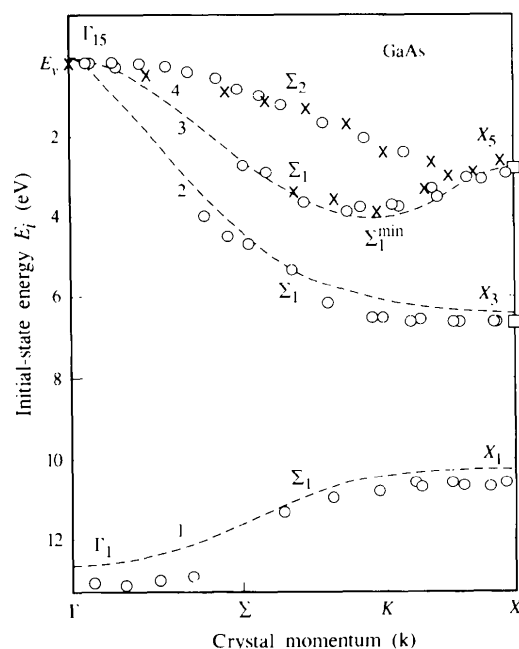
**Figure 6**

Angle-resolved photoelectron spectra from 1T-TaS<sub>2</sub> taken with the two geometrical arrangements shown in the lower part of the figure. The spectra are polar plots of photocurrent versus azimuthal angle about the crystal normal, which is the  $c$  axis of the crystal (Smith, Traum *et al.*, 1976).

Higher beam currents also allowed the photoelectron spectroscopy of low-density samples, *e.g.* atomic or molecular vapors and adsorbed overlayers of the order of a monolayer thick. In the latter case, if the molecules are adsorbed with a particular orientation, angle-resolved photoelectron spectroscopy often can determine the orientation. The first example (Smith, Anderson & Lapeyre, 1976), CO adsorbed on Ni (001), made use of the polarization of the synchrotron radiation in measuring angle-resolved photoelectron spectra at several angles from the surface normal with both  $s$ - and  $p$ -polarizations. Comparison with gas-phase spectra (Gustafsson, Plummer, Eastman & Freeouf, 1975) and calculated spectra led to the conclusion that the CO molecule adsorbed with its axis normal to the surface and that the C end was closest to the substrate.

Kemny, Samson & Starace (1977) worked with Xe vapor, determining the branching ratio for  $5p$  photoionization in the spectral range of the  $5s$ - $6p$  resonance (20.95 eV) by measuring the photocurrent from each final state,  $^2P_{3/2}$ ,  $^2P_{1/2}$ , as a function of photon energy. The resonance increased the branching ratio from 1.55 (the statistical ratio is 2.0) to a peak value of 8.8. As the beam currents increased, the sophistication of the experiments also increased. Measurements of the anisotropy of photoemission ( $\beta$ ) of atomic and molecular vapors led to elucidation of many-body effects in Xe (Krause, Carlson & Woodruff, 1981) and confirmation of a suspected shape resonance in CO<sub>2</sub> (Carlson *et al.*, 1981).

Higher currents also allowed modulation spectroscopy to be extended into the vacuum ultraviolet region. This also required improving the positional stability of the beam, which was accomplished. In modulation spectroscopy a



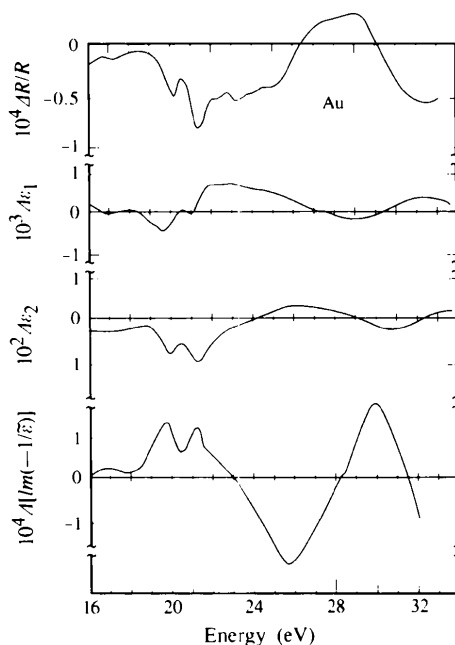
**Figure 7**

Comparison of calculated and measured energy bands in GaAs along the [110] direction (Chiang *et al.*, 1979, 1980).



periodic perturbation is applied to the sample, typically at an audio frequency or lower, and the modulation of the transmitted or reflected beam is detected. The incident beam intensity and the instrumental response functions cancel from the spectrum of the ratio of the modulated signal to the unmodulated signal. This spectrum, of the order of  $10^{-2}$  to  $10^{-5}$ , represents the optical response of the system to the perturbation, which may be an electric field, a uniaxial stress, or a temperature change. The spectral shape typically resembles a linear combination of the first and second derivatives with respect to the energy of the unmodulated spectrum, but with energy-dependent weightings, because not all initial and final states respond identically to the perturbation. Both modulation spectra and derivatives of normal spectra taken numerically have, in the absence of other sources of noise and of false signals, a signal-to-noise ratio scaling as the square root of the detected current. Thus, for both types of spectra a large photon flux is desirable. Modulation spectroscopy in the 1–6 eV region contributed greatly to the understanding of the electronic structure of many types of materials, but it was felt that it would be of limited utility at higher photon energies because of broadening due to short photohole lifetimes.

The first modulation spectra (Olson, Piacentini & Lynch, 1974) were of thermoreflectance spectra of Au, which were spectra of the derivative of the reflectance with respect to temperature. Kramers–Kronig analysis gave spectra of the temperature derivatives of the real and imaginary parts of the dielectric function and of the electron energy-loss function, were derived from a dispersion analysis of  $\Delta R/R$  (Olson *et al.*, 1974).

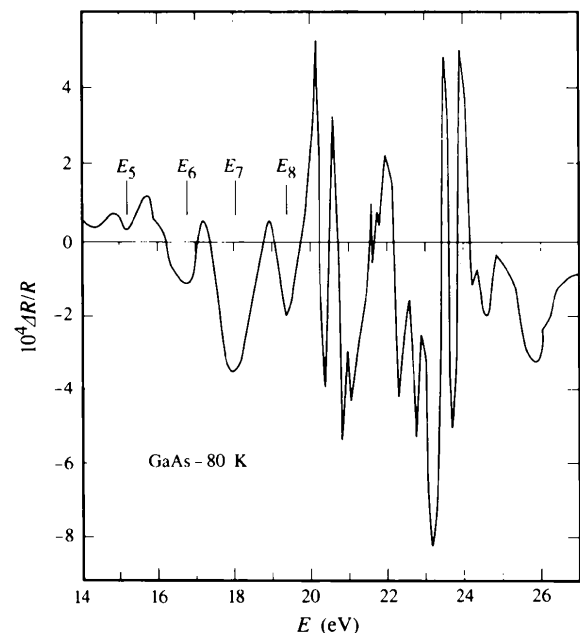


**Figure 8**

Part of the thermomodulation spectra of a film of Au.  $\Delta R/R$ , the temperature derivative of the logarithm of the reflectance, was measured and the other spectra, the temperature derivatives of the real and imaginary parts of the dielectric function and of the electron energy-loss function, were derived from a dispersion analysis of  $\Delta R/R$  (Olson *et al.*, 1974).

the dielectric function. These are shown in Fig. 8. (The spectra extend down to 5 eV.) The rather sharp structures near 20 eV are the result of transitions from the  $5d$  bands to a very flat band about 15 eV above the Fermi level. This band is based on  $5f$  levels. Evidently it has a narrow width due to a long lifetime.

Electroreflectance spectra had provided extremely sensitive and precise determination of interband critical points in semiconductors. Such spectroscopy was extended above 5 eV on GaAs and GaP by Aspnes, Olson & Lynch (1975). The spectra were taken through a very thin film electrode of Ni or Au, forming a Schottky barrier in which the modulation field was localized. Fig. 9 shows a typical spectrum. Its interpretation may be found in the original paper. Transitions between valence and conduction bands dominate below 20 eV, while above 20 eV, transitions from the Ga  $3d$  spin-orbit split core levels to various conduction-band minima dominate. Spectra for transitions from a core level to various inequivalent conduction-band local minima can be used to obtain the energies of these minima with respect to the lowest minimum, something difficult to do in valence-conduction-band spectroscopy because of the dispersion in both valence and conduction bands. This was performed for GaAs (Aspnes, Olson & Lynch, 1976) using electroreflectance, with the result that the first conduction-band local minima above the lowest ( $\Gamma$ ) were at the  $L$  points, not the  $X$  points as had been believed previously. The  $X$  minima were 170 meV higher than the  $L$  minima. This explained a number of puzzling features in several previous measurements on GaAs.



**Figure 9**

Electroreflectance spectrum of GaAs taken through an Ni thin-film electrode. The features labelled  $E$  are from interband critical points. The spectrum above 20 eV arises from transitions between the Ga  $3d$  spin-orbit-split levels and various conduction-band critical points (Aspnes *et al.*, 1975).

Magnetic circular dichroism spectroscopy was extended to over 9 eV, the limit being set by the transmission of the stress-plate modulator and the LiF windows on the sample chamber for vapor samples. The first spectra, on benzene vapor, helped settle a controversy in the interpretation of the absorption spectra of benzene (Snyder, Lund, Schatz & Rowe, 1981); see Fig. 10.

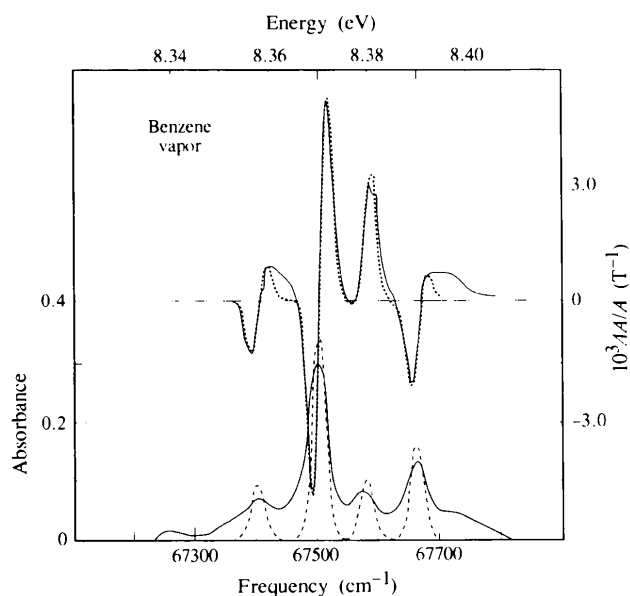
Fluorescence spectroscopy began rather early at SRC. The undispersed radiation from Tantalus was used by Elias, Heaps & Yen (1973) to measure the spectrum of photoexcited luminescence from  $\text{Ce}^{3+}$  and  $\text{Pr}^{3+}$  as substitutional impurities for  $\text{La}^{3+}$  in  $\text{LaF}_3$ . The 4 ns pulses from Tantalus were used to measure the fluorescence (3050 Å) lifetime (20 ns) of photoexcited  $\text{Ce}^{3+}$  in  $\text{LaF}_3$  by measuring the fluorescence decay intensity as a function of time between pulses of synchrotron radiation (Heaps, Hamilton & Yen, 1973).

Photoabsorption spectroscopy of gas-phase samples began in 1971 with spectra of Ar in the 180–700 Å region, which includes the  $3s$ – $np$  photoexcitations (Carlson, Judge, Ogawa & Lee, 1973) and absorption spectra of silane,  $\text{SiH}_4$ , spanning the Si  $2p$  threshold (Hayes, Brown & Kunz, 1971). Gas-phase photoemission began early with the measurements of the asymmetry parameter  $\beta$  for benzene vapor, using two unpolarized helium emission lines and the strongly polarized monochromated synchrotron radiation from Tantalus (Kinsinger & Taylor, 1972/1973). This parameter describes the angular distribution of photoelectrons from a gas of atoms or molecules. It is related to atomic or molecular matrix elements and is independent of the electric dipole matrix element. At issue at the time was

the question of how much the photon-energy dependence of the anisotropy had affected the relative yield measurements previously made with the two He lines. The measurements from Tantalus showed that  $\beta$  depended rather strongly on the photon energy and on the electron kinetic energy.

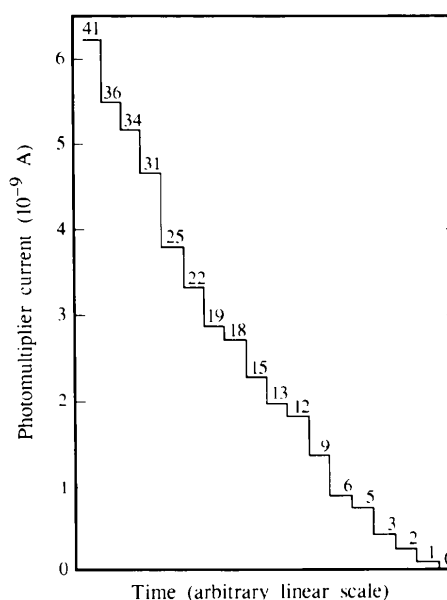
Earlier measurements of cross section for atoms and molecules were extended from total cross sections to partial cross sections. An example was the determination of the cross section for the ionization of He to the  $n = 2$  state of  $\text{He}^+$ , using the fluorescent 40.8 eV photon to identify the absorptive transition (Woodruff & Samson, 1980). To separate the  $2s$  and  $2p$  contributions, the differences in lifetimes were used (Woodruff & Samson, 1982). The  $2p$  decayed nearly instantly, while the  $3s$  lifetime is 2.2 ms. An applied electric field mixed the  $2s$  and  $2p$  levels, leading to decay by both before the atoms left the sampling region. The difference between yield spectra with and without the field allowed the separation to be effected over a 67–128 eV range of exciting photon energies.

An unusual use of Tantalus was Fairchild's calibration of a photomultiplier for use in stellar observation (1100–3000 Å) from rockets (Fairchild, 1971). The synchrotron radiation spectrum can be calculated in closed form, hence used for calibrations, but the flux is directly proportional to the beam current, which may not be known with sufficient accuracy. By using a very small circulating beam and monitoring the photomultiplier anode current as a function of time, the loss of individual electrons from the beam could be seen (Fig. 11). The current was obtained from the accurately known orbital frequency and the exact number of electrons at the time of the measurement.



**Figure 10**

Absorbance ( $A$ ), lower solid curve (left-hand scale), and magnetic circular dichroism spectrum  $[(A_L - A_R)/A]$ , upper solid curve (right-hand scale) of benzene vapor. The dashed curves are Gaussian fits to the spectra (Snyder *et al.*, 1981).



**Figure 11**

Photomultiplier current *versus* time as electrons were lost from a low-current beam in Tantalus. The numbers on the steps are the number of electrons stored in the ring (Fairchild, 1971; F. C. Brown, private communication).

#### 4. The end of Tantalus

Tantalus was decommissioned in 1987 because Aladdin, the new 800–1000 MeV storage ring at SRC, was operating reliably. However, that was not yet the end of Tantalus, for in the summer of 1988, J. A. R. Samson requested that it be run for experiments in atomic and molecular fluorescence using the undispersed beam for excitation (Samson, Chung & Lee, 1988, 1991; Meier, Samson, Chung, Lee & He, 1991). It was run for them for six weeks, although, having been decommissioned, its operation could not be financed by the SRC operations contract; the users had to pay the costs of operation. In the early 1990's pressure from the University of Wisconsin to use the Tantalus vault for other purposes led to the disassembly of the storage ring in 1995. One half of Tantalus, the r.f. cavity, and the original University of Illinois beamline, is now in the possession of the Smithsonian Institution, but it is housed in a warehouse, and is not on display.

#### 5. The legacy of Tantalus

As the first storage ring operated exclusively for the production of synchrotron radiation, Tantalus was a model for how the operations staff and the users, often from many institutions with a variety of institutional cultures, interacted. SRC set early precedents for the introduction of new users to the use of synchrotron radiation. It also showed how the three categories of synchrotron radiation user could be accommodated: users who owned a beamline and worked nearly continuously at the site, users who used 'public' beamlines, but who were steady visitors, and intermittent users whose background and expertise may have been in areas unrelated to the use of synchrotron radiation, but who had a need for synchrotron radiation, possibly only for a 'one-shot' experiment. Many young scientists from all over the world spent time at Tantalus, usually as postdoctoral research associates of one of the regular user groups. Often they were resident in the Madison area. Many of these went on to distinguished careers in science, often as users of synchrotron radiation, becoming leaders in their scientific communities. Examples still active in the synchrotron radiation community include Alex Bradshaw, Wolfgang Eberhardt, Wolfgang Gudat, Giorgio Margaritondo, Nils Mårtensson, Bruno Reihl, Renzo Rosei, Bernd Sonntag and Phil Woodruff, along with many others currently active in research with synchrotron radiation in the US.

SRC ran Tantalus on an amazingly low budget. The University of Wisconsin financed the utility costs, and some space and salaries. The National Science Foundation operating contract financed the rest of the operations. The users, of course, were funded by their own grants and by their home institutions. After 1976, between 50 and 100 papers based on work performed at Tantalus were published each year. It was often stated that on some of the most productive years of the operations of Tantalus, the annual

page charges for the publications of the users exceeded the operating costs of Tantalus. This seems to have been true, using certain interpretations of accounting rules.

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